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Experimental and theoretical study of the gas-water two phase flow through a conductance multiphase Venturi meter in vertical annular (wet gas) flow

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Abstract
Annular gas-liquid two phase flow is widely encountered in the nuclear industry.
Various combinations of techniques have been employed in annular gas-liquid two phase flows to measure the flow parameters (e.g. liquid film thickness, gas volume fraction and the phase flow rates). One of the most useful techniques which has proven attractive for many multiphase flow applications is the electrical conductance technique. This paper presents an advanced Conductance Multiphase Venturi Meter (CMVM) which is capable of measuring the gas volume fractions at the inlet and the throat of the Venturi. A new model was investigated to measure the gas flow rate. This model is based on the measurement of the gas volume fractions at the inlet and the throat of the Venturi meter using a conductance technique rather than relying on the prior knowledge of the mass flow quality x. We measure conductance using two ring electrodes flush with the inner surface of the Venturi throat and two ring electrodes flush with the inner surface of the Venturi inlet. The basic operation of the electrical conductance technique in a multiphase flow is that the conductance of the mixture depends on the gas volume fraction in the water. An electronic circuit was built and calibrated to give a dc voltage output which is proportional to the conductance of the mixture which can then be related to the water film thickness in annular flow (and hence to the gas volume fraction). It was inferred from the experimental results that the minimum average percentage error of the predicted gas mass flow rates (i.e. -0.0428 %) can be achieved at the optimum gas discharge coefficient of 0.932.

Keywords: Venturi meter, electrical conductance technique, annular flow.

1. Introduction

Annular gas-liquid two phase flow is widely occurred in flow channels of nuclear processes. In water continuous multiphase flow, the electrical conductance technique has proven attractive for many industrial applications. The idea behind this technique is that an electric current is made to flow through the gas-water mixture, between two ring electrodes in contact with the mixture, and the resultant measured voltage drop is proportional to the mixture conductance. The gas volume fraction can then be determined from this measured mixture conductance.

Differential pressure devices can be used in multiphase flow metering. The most common differential pressure device is the Venturi meter, but orifice plates have also been used widely. The advantage of the Venturi meter over the orifice plate is that the Venturi meter is much more predictable and repeatable than the orifice plate for a wide range of flow conditions. Further, the smooth flow profile in a Venturi meter reduces frictional losses which (i) increases the reliability of the device and (ii) improves the pressure recovery. An interesting result, relevant to this paper was obtained by (Malayeri et al. 2001) who studied the behaviour of gas liquid upward

bubbly flow through a vertical Venturi using a gamma densitometer and found that the void fraction at the throat was always less than at the inlet of the Venturi at fixed water flow rate over a range of gas flow rates.
Considerable theoretical and experimental studies have been published to describe mathematical models of Venturis in multiphase flow applications. The study of multiphase flow through contraction meters is described for example by (Murdock 1962; R. V. Smith & Leang 1975; Chisholm 1967; Chisholm 1977; Lin 1982; de Leeuw 1994; Steven 2002). All of these correlations depend either on the mass flow quality, x or empirical constants. None of these models depend on the measurements of the gas volume fraction at the inlet and the throat of the Venturi/orifice meter. However, online measurement of mass quality x is difficult and not practical in multiphase flow applications.

This paper develops a new advanced design of a conductance multiphase Venturi meter (CMVM) which is capable of measuring the gas volume fraction at the inlet and the throat of the Venturi in annular gas-water two phase flows. The basic operation of the electrical conductance technique in a multiphase flow is that the conductance of the mixture depends on the gas volume fraction in the water. An electronic circuit was built and calibrated to give a dc voltage output which is proportional to the conductance of the mixture and which can then be related to the water film thickness in annular flow (and hence to the gas volume fraction). A new separated two phase flow model through a vertical Venturi meter which depends on the measurement of gas volume fractions at the inlet and the throat of the Venturi was investigated.

2. Mathematical models and correlations

2.1 Previous correlations through contraction meters in a separated flow

Some of the correlations found in literature pertinent to the present study are listed below.

2.1.1 Murdock correlation

Murdock (1962) studied the two phase flow through an Orifice plate meter and his work was not restricted only to wet gas flows. Murdock developed a rational equation modifying the single phase equation by introducing an experimental constant (correction factor). Murdock's correlation considers two phase flow to be separated flow and he computed the total mass flow rate using an empirical constant (equal to 1.26) and by assuming that the quality of the mixture is known. The correction factor in Murdock's correlation was solely a function of the modified version of Lockhart-Martinelli parameter X_{mod} which is defined as the ratio of the superficial flows momentum pressure drops (and not the friction pressure drops as in the original definition by Lockhart-Martinelli parameter). The modified Lockhart-Martinelli parameter is given by;

$$X_{\text{mod}} = \sqrt{\frac{\Delta P_w}{\Delta P_g}} = \left(\frac{\dot{m}_w}{\dot{m}_g}\right)\left(\frac{k_g}{k_w}\right)\sqrt{\frac{\rho_g}{\rho_w}} = \left(\frac{1-x}{x}\right)\left(\frac{k_g}{k_w}\right)\sqrt{\frac{\rho_g}{\rho_w}} \quad (1)$$

where ΔP_w and ΔP_g are the differential pressures when the liquid and gas phases respectively flow alone, $\dot{m}_w$ and $\dot{m}_g$ are the water and gas flow rates respectively,

k_g and k_w are the gas and water flow coefficients, ρ_g and ρ_w are the gas and water density respectively and x is the mass flow quality ($x = \dot{m}_g /(\dot{m}_g + \dot{m}_w)$). The gas mass flow rate in two phase flow from Murdock's correlation can be written as;

$$\dot{m}_g = \frac{A_t k_g \sqrt{2\Delta P_{TP}\rho_g}}{1 + 1.26\frac{1-x}{x}\frac{k_g}{k_w}\sqrt{\frac{\rho_g}{\rho_w}}} = \frac{A_t k_g \sqrt{2\Delta P_{TP}\rho_g}}{1 + 1.26 X_{\text{mod}}} \tag{2}$$

where ΔP_{TP} is the two phase pressure drop.

2.1.2 Chisholm correlation

Chisholm (1967, 1977) studied two phase separated flow through a sharp edge orifice plate. The Chisholm correlation is a function of the two phase pressure drop and the modified Lockhart-Martinelli parameter. The gas mass flow rate in the Chisholm correlation can be written as;

$$\dot{m}_g = \frac{k_g A_t \sqrt{2\Delta P_{TP}\rho_g}}{\sqrt{1 + C X_{\text{mod}} + X_{\text{mod}}^2}} \tag{3}$$

where A_t is the total flow area during two phase flow and C is the 'Chisholm parameter' and is given (in terms of a slip ratio S) by;

$$C = \frac{1}{S}\sqrt{\frac{\rho_w}{\rho_g}} + S\sqrt{\frac{\rho_g}{\rho_w}} \tag{4}$$

2.1.2 Lin correlation

Lin (1982) developed his model on the basis of a separated flow model (for general stratified two phase flow) and compared his model against the experimental data. This comparison shows that the Lin model can be used to calculate the flow rate or the quality of gas-liquid mixture in the range 0.00455 to 0.328 of the density ratio ρ_g/ρ_w, and in the pipe size ranging from 8 to 75 mm. The Lin correction factor K is given by;

$$\begin{aligned} K = {} & 1.48625 - 9.26541\left(\frac{\rho_g}{\rho_w}\right) + 44.6954\left(\frac{\rho_g}{\rho_w}\right)^2 - 60.6150\left(\frac{\rho_g}{\rho_w}\right)^3 \\ & - 5.12966\left(\frac{\rho_g}{\rho_w}\right)^4 - 26.5743\left(\frac{\rho_g}{\rho_w}\right)^5 \end{aligned} \tag{5}$$

The gas mass flow rate in Lin correlation can be written as;

$$\dot{m}_g = \frac{k_w A_t x\sqrt{2\Delta P_{TP}\rho_w}}{K(1-x) + x\sqrt{\frac{\rho_w}{\rho_g}}} = \frac{k_w A_t \sqrt{2\Delta P_{TP}\rho_g}}{K\left(\frac{\dot{m}_w}{\dot{m}_g}\right)\sqrt{\frac{\rho_g}{\rho_w}} + 1} \tag{6}$$

2.2. A new Separated Two Phase Flow Model through a Venturi Meter

It is clear from the previous models that they all depend on prior knowledge of the mass flow quality *x*. Online measurement of *x* is very difficult and not practical in nearly all multiphase flow applications. The new model depends on measurement of the gas volume fractions at the inlet and the throat of the Venturi meter rather than relying on prior knowledge of the mass flow quality. In a separated flow, the assumption that the velocities of the phases are equal is invalid and the slip ratio *S* is not unity. In other words, each phase flows separately with different velocity. A new separated two phase flow model through a Venturi meter has been investigated. This model is based on the fact that each phase flows separately as shown in Fig. 1. Fig. 2 shows how the gas volume fractions are defined through a Venturi meter.
For the gas phase, the Bernoulli equation can be written as;

$$P_1 + \frac{1}{2}\rho_{g1}U_{g1}^2 = P_2 + \frac{1}{2}\rho_{g2}U_{g2}^2 + \Delta P_H \quad (7)$$

where *P* is static pressure, ρ is density, *U* is velocity and ΔP_H is the magnitude of the hydrostatic head loss between the inlet and the throat of the Venturi (i.e. between pressure tapping separation). The subscripts 1, 2 and g refer to the inlet, throat and the gas phase respectively. Any frictional pressure losses will be accounted for in a discharge coefficient at a later stage.

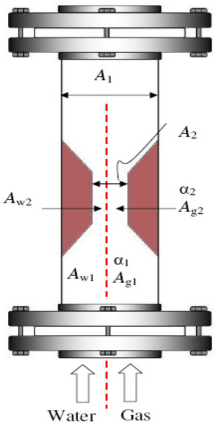


Figure 1: Gas-water two phase flow through a Venturi meter

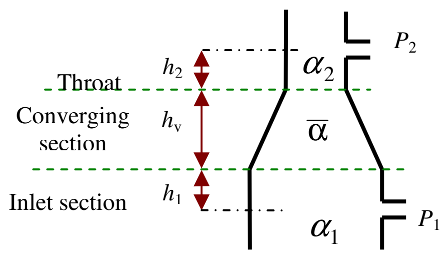


Figure 2: Inlet, converging and throat sections of the Venturi meter

The gas density at the inlet of the Venturi ρ_{g1} is related to the gas density at the throat of the Venturi ρ_{g2} by the following equation;

$$\frac{P_1}{\rho_{g1}^{\gamma}} = \frac{P_2}{\rho_{g2}^{\gamma}} \quad (8)$$

where γ is the adiabatic index.
Including Eq. (8) in an equation for mass continuity gives;

$$U_{g2} = U_{g1}\left(\frac{\alpha_1 A_1}{\alpha_2 A_2}\right)\left(\frac{P_2}{P_1}\right)^{\left(-1/\gamma\right)} \quad (9)$$

where α_1 and α_2 are the gas volume fractions at the inlet and the throat of the Venturi. Combining equations (7) (8) and (9), and introducing a discharge coefficient C_{dg} for the gas phase, enables derivation of the following expression for the gas mass flow rate.

$$\dot{m}_{g,predicted} = C_{dg} \frac{\left(2\rho_{g1}\{\Delta P_{TP} - \Delta P_H\}\right)^{\frac{1}{2}} A_1 A_2 \alpha_1 \alpha_2}{\left\{(\alpha_1 A_1)^2 \left(\frac{P_2}{P_1}\right)^{\frac{-1}{\gamma}} - (\alpha_2 A_2)^2\right\}^{\frac{1}{2}}} \tag{10}$$

The hydrostatic head loss term ΔP_H in Eq. (10) can be calculated by making an assumption that the mean gas volume fraction in the converging section is $\overline{\alpha}$ where;

$$\overline{\alpha} = \frac{\alpha_1 + \alpha_2}{2} \tag{11}$$

The hydrostatic head loss term can now be expresses as follows; (using the position of the pressure tappings shown in Fig. 2)

$$\Delta P_H = gh_1\{\rho_w(1-\alpha_1) + \rho_{g1}\alpha_1\} + gh_v\{\rho_w(1-\overline{\alpha}) + \overline{\rho}_g\overline{\alpha}\} + gh_2\{\rho_w(1-\alpha_2) + \rho_{g2}\alpha_2\} \tag{12}$$

where $\overline{\rho}_g$ is the average gas density between inlet and the Venturi throat, h_1, h_2 and h_v are the heights defined in Fig. 2. The gas density at the throat section ρ_{g2} is given by;

$$\rho_{g2} = \rho_{g1}\left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}} \tag{13}$$

The gas density at the inlet can be obtained from Eq. (14);

$$\rho_{g1} = \frac{P_1}{rT_1} \tag{14}$$

where P_1 and T_1 are the absolute pressure and temperature at inlet section respectively and r is the specific gas constant and is given by;

$$r = \frac{1000R}{M_m} \tag{15}$$

where R is the universal gas constant and M_m is the relative molecular mass of the gas. The gas discharge coefficient C_{dg} can be expressed as;

$$C_{dg} = \frac{\dot{m}_{g,ref}}{\dot{m}_{g,predicted}} \tag{16}$$

where $\dot{m}_{g,predicted}$ is the predicted value of the gas volume flow rate and $\dot{m}_{g,ref}$ is the reference gas mass flow rate obtained from Variable Area Flowmeter (VAF).

It is clear that, the advantage of the new model (Eq. 10) over the previous models is that it does not require prior knowledge of mass flow quality *x*. In other words, the new model depends only on the measurement of α_1 and α_2 which makes the measurement technique more practical than those used previously.

3. Design of the conductance multiphase flow meter.

To determine the gas flow rate in Eq. (10), the measurement of the gas volume fractions at the inlet and the throat (α_1 and α_2) must be achieved. To do so, a new conductance multiphase flow meter was designed and constructed (Fig. 3 and Fig. 4). This meter consists of two sections; the conductance Inlet Void Fraction meter (IVFM) and the Conductance Multiphase Venturi Meter (CMVM) which is capable of measuring the gas volume fractions at the inlet and the throat of the Venturi (α_1 and α_2 respectively). Four ring electrodes were used (two at the inlet section and two at the throat section). The ring electrodes were designed to be flush mounted to the inner surfaces of the inlet and the throat of the Venturi) in order to avoid flow disturbances. One of the most advanced features of this design is that, all parts can be assembled/disassembled easily including the threaded flanges. Another advantage of this design is that it is very straightforward to change the throat section (Hasan & Lucas 2008).

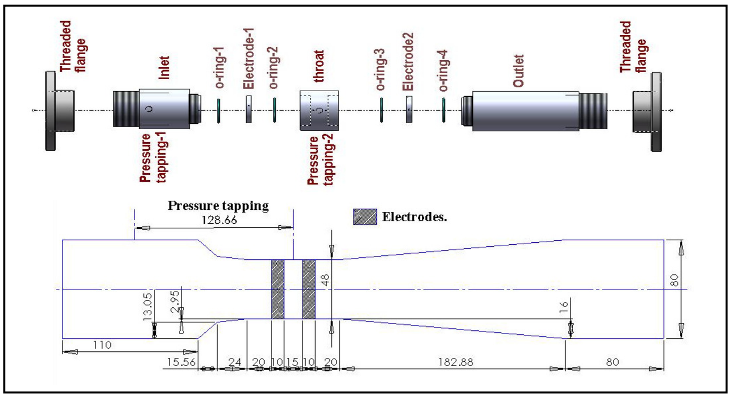


Figure 3: The design of the conductance multiphase Venturi meter (CMVM)

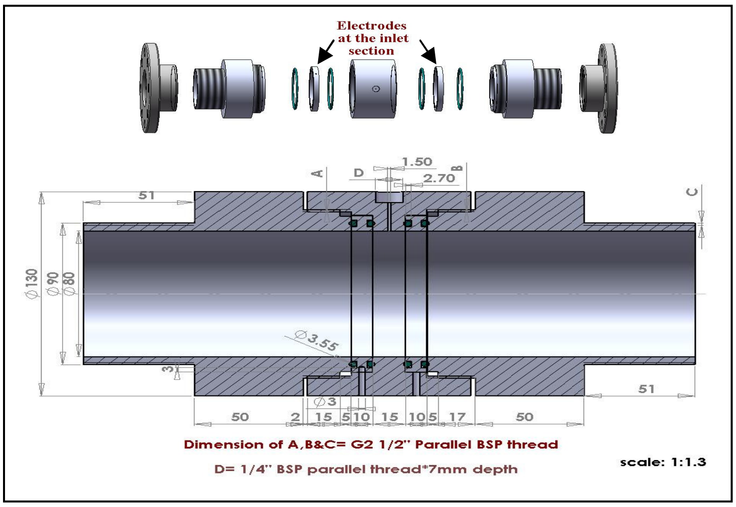
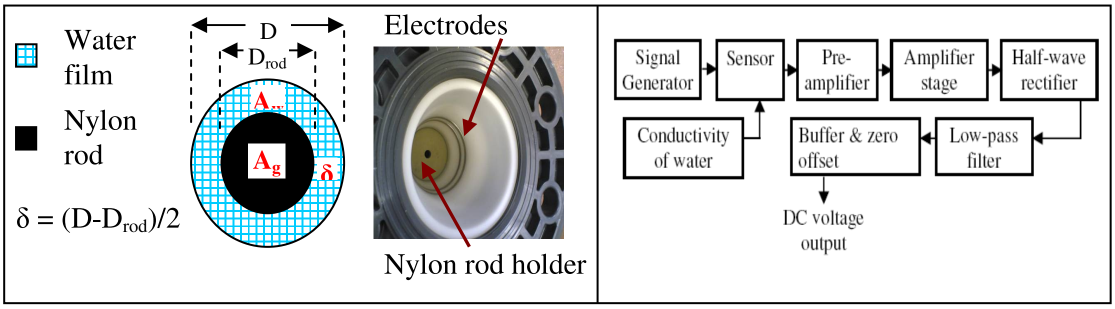


Figure 4: The design of the conductance Inlet Void Fraction Meter (IVFM)

4. Bench Tests on the Conductance meter (CMVM and IVFM)

Before the CMVM and IVFM were used dynamically in the flow loop as a multiphase flow meter, a number of experimental bench testing procedures were carried out. A bench test rig was designed and built in order to calibrate the conductance measurement systems of both the CMVM and IVFM. For the CMVM vertical experiments (simulating annular flow), different diameters of nylon rods were inserted through the throat of the Venturi and the gap between the outer surface of the rod and the inner surface of the Venturi was filled with water, representing the water film in a real annular flow situation as shown in Fig. 5a. The complete block diagram of the measurement electronics system is also shown in Fig. 5b. At the beginning of the experiment the zero offset stage was adjusted to give a zero output voltage when no water was present at the throat of the Venturi. The amplifier stage was then adjusted to give a maximum voltage when the region between the electrodes at the Venturi throat was completely filled with water. A similar procedure was used to calibrate conductance measurement system of the IVFM.



(a) (b)

Figure 5: Bench test experimental setup and the block diagram of the measurement electronics system

4.1.1 Results from Bench Tests

As described above, bench tests were performed by inserting non-conductive nylon rods with different diameters through the CMVM and IVFM. The dc output voltages from the electronic measurement circuits were recorded which were related to the liquid film thickness (and hence the gas volume fractions) in the IVFM and at the throat of the Venturi. The mixture resistance (and hence the conductance of the mixture) can be practically measured from the pre-amplifier stage shown in Fig. 5b. It should be noted that the static and dynamic measurements were taken at the laboratory conditions in which the temperature of the water was kept constant at an average value of 22.5 ^{o}C . Measurement of the water conductivity taken using a conventional conductivity meter showed that the water conductivity took as value of 143 μScm^{-1} for all of the experiments described in this paper.

Fig. 6 and Fig. 7 show the calibration curves of the inlet and the throat of the conductance Venturi meter.

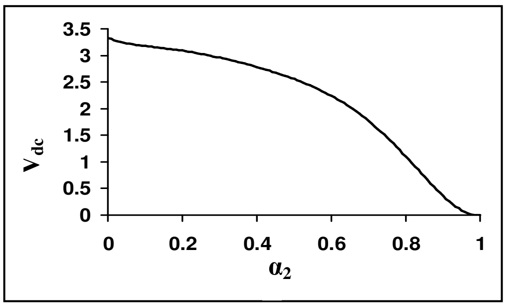


Figure 6: Calibration curve for the CMVM

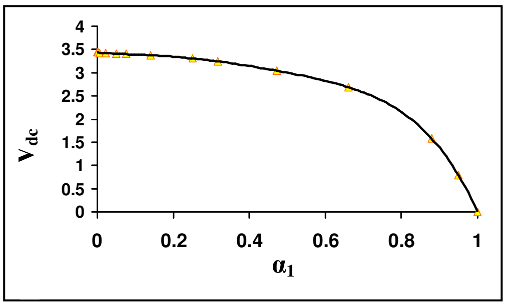


Figure 7: Calibration curve for the IVFM

5. Multiphase flow loop and experimental setup

One of the multiphase flow loops at the University of Huddersfield is capable of providing gas-water annular flows (see Fig. 8). This flow loop has an 80 mm inner diameter and a 3 meter long test section. The test section can be vertical, horizontal or inclined at any intermediate angle but it was used in the vertical orientation for the experiments described in this paper. A range of auxiliary test equipment is available for use with the flow loop including differential pressure sensors, temperature sensors, a gauge pressure sensor, a turbine flow meter, gas flow meters and multiphase conductance meters. The temperature was kept constant at an average value of 22.5 °C.

A schematic diagram of the multiphase test section with interfacing system is shown in Fig. 9.

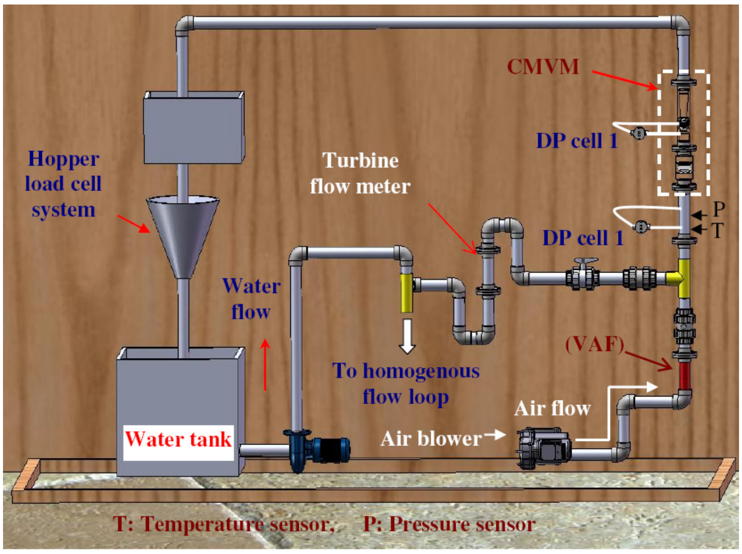


Figure 8: A schematic diagram of the gas-water annular flow loop

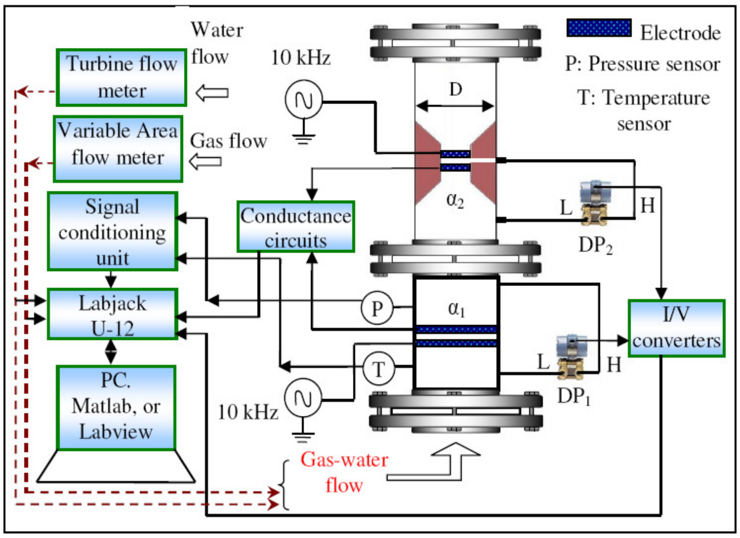


Figure 9: A schematic diagram of the multiphase test section with interfacing system

6. Experimental results

Experiments were carried out in vertical upward gas-water flows using the conductance multiphase Venturi meter. Eighty five different flow conditions were tested. The summary of the flow conditions are given in table 1.

Table 1: Summary of the flow conditions

Data set no.	*Superficial gas velocity* U_{sg} (ms^{-1})	*Superficial water velocity* U_{sw} (ms^{-1})
1	6.919 to 8.566	0.010417
2	6.350 to 8.259	0.016315
3	6.837 to 8.323	0.015312
4	6.451 to 7.903	0.012351

To determine the gas flow rate in Equation (3.66) the measurement of the gas volume fraction at the inlet and the throat of the Venturi in annular (wet gas) flow ($\alpha_{1,wg}$ and $\alpha_{2,wg}$) must be achieved. To do so, a new conductance multiphase Venturi meter was designed and constructed (see section 4.3). It is clear from the model described in section 3.2.2 that the measurement of the gas volume fraction at the inlet and the throat of the Venturi, $\alpha_{1,wg}$ and $\alpha_{2,wg}$ respectively in annular (wet gas) flow enables the gas mass flow rate through a Venturi, $\dot{m}_{g,wg}$ to be determined.

de Leeuw (1994) analyzed his data based on the Froude number rather than velocities. The gas Froude number Fr_g in terms of the superficial gas velocity U_{sg} is defined as;

$$Fr_g = \frac{U_{sg}(\rho_g / [\rho_w - \rho_g])^{0.5}}{[gD]^{0.5}} \tag{17}$$

A good predication of the gas velocity at the throat of the Venturi U_{g2} can be obtained from the gas Froude number as shown in Fig. 10. This may further simplify the model investigated in this paper.

The gas discharge coefficient in a vertical annular (wet gas) flow through a Conductance Multiphase Venturi Meter (CMVM), C_{dg} is given by equation (16). It is clear from Fig.11 that the gas discharge coefficient C_{dg} for four sets of data can be treated as independent of the reference gas mass flow rate $\dot{m}_{g,ref}$ and can be averaged at 0.932. This value of the discharge coefficient represents the optimum value in which a minimum average percentage error in the predicted gas mass flow rate can be achieved (see also figures 14 to 16).

The predicted gas mass flow rate $\dot{m}_{g,predicted}$ can be determined using Eq. (10). The comparison between the reference gas mass flow rate and the predicted gas mass flow rate for $C_{dg} = 0.932$ is shown in Fig.11. The reference gas mass flow rate $\dot{m}_{g,ref}$ was obtained from a Variable Area Flow meter (VAF) as shown in Figures 8 and 9. The solid lines in Fig. 12 represent the reference lines (45^o lines).

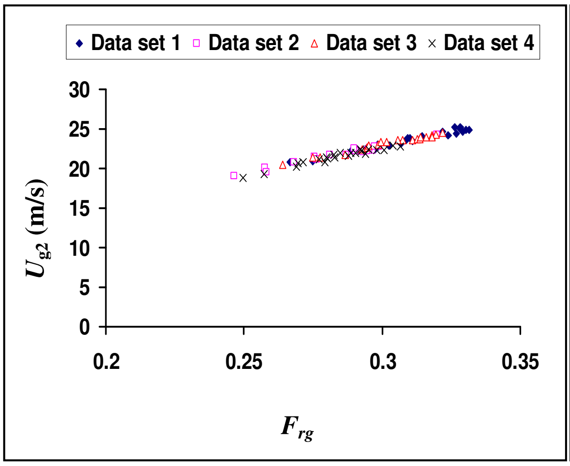


Figure 10: The relationship between the gas velocity at the throat and Froude number

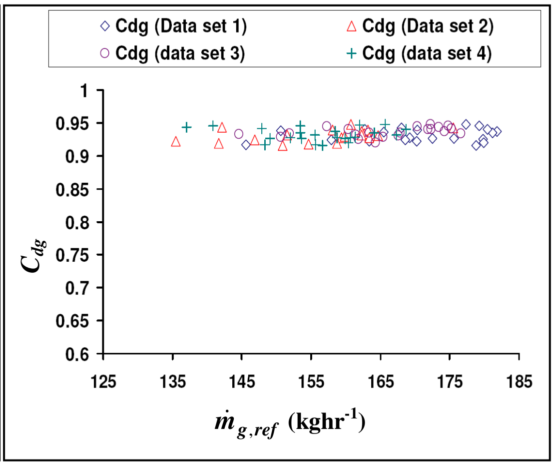


Figure 11: Gas discharge coefficient C_{dg} of the Conductance Multiphase Venturi meter (CMVM)

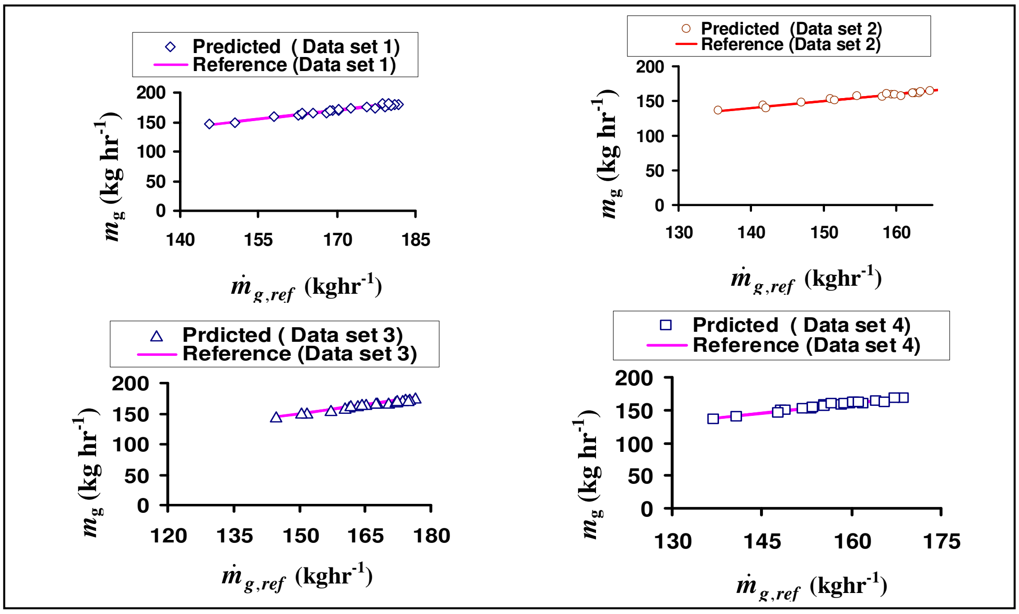


Figure 12: Comparison between reference and predicted gas mass flow rates

Fig. 13 shows the variations of the gas volume fraction at the inlet and the throat of the Venturi in a vertical annular (wet gas) flow. It can be seen from Fig.13 that, in general, α_1 (at the Venturi inlet) is greater than α_2 (at the Venturi throat). This difference becomes more visible at lower water flow rates (data set # 1).

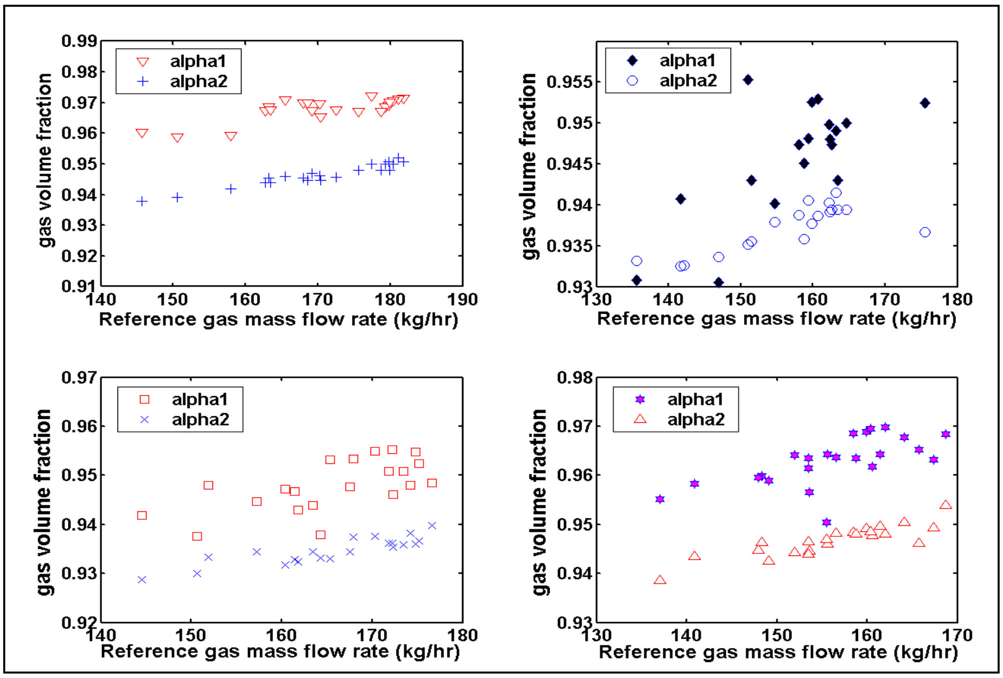


Figure 13: Variations of the gas volume fraction at the inlet and throat of the Venturi

The percentage error in the predicted gas mass flow rates ε is obtained from the predicted gas mass flow rate $\dot{m}_{g,predicted}$ (obtained using measurements from the CMVM and the model described in Equations (1) to (16)) and from the reference gas mass flow rate $\dot{m}_{g,ref}$ obtained from a conventional variable area flowmeter (VAF) using;

$$\varepsilon = \left(\frac{\dot{m}_{g,predicted} - \dot{m}_{g,ref}}{\dot{m}_{g,ref}} \right) \times 100\,\% \tag{17}$$

In order to measure the $\dot{m}_{g,ref}$ in Eq. (17), the absolute pressure P_1 and the absolute temperature T_1 must be measured at the upstream section of the Venturi. Measurements of P_1 and T_1 enables the gas density ρ_{g1} at the inlet of the Venturi to be determined (see Equations (14) and (15)).The reference gas volume flow rate $Q_{g,ref}$ obtained from the VAF can be then converted into the reference gas mass flow rate $\dot{m}_{g,ref}$ using;

$$\dot{m}_{g,ref} = \rho_{g1} Q_{g,ref} \tag{18}$$

where $Q_{g,ref}$ is the reference gas volume fraction obtained from the variable area flowmeter (VAF) before the gas phase enters the two-phase flow test section.

Figures 14 to 16 show the percentage error of the theoretical gas mass flow rates, ε for C_{dg} = 0.92, 0.932 and 0.933. It is clear from these figures that the minimum average percentage error in the predicted gas mass flow rate $\dot{m}_{g,predicted}$ (i.e. -0.0428 %) can be achieved at C_{dg} =0.932. The standard deviations are also shown in Figures 14 to 16. At C_{dg} =0.932, the ε is approximately varied within ± 1.8% (see Fig. 15). As the C_{dg} increased to 0.933 the variations of the ε is approximately within ± 1.9% (see Fig. 16).

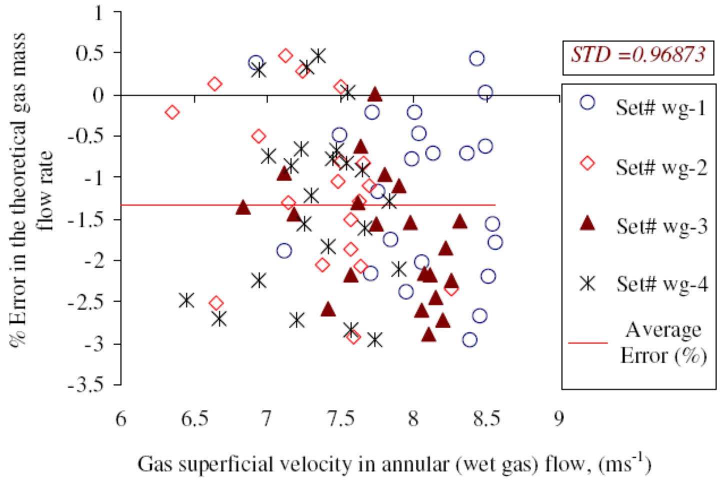


Figure 14: The percentage error in the predicted gas mass flow rates for all sets of data ($C_{dg,wg} = 0.92$ and the standard deviation, *STD* = 0.96873)

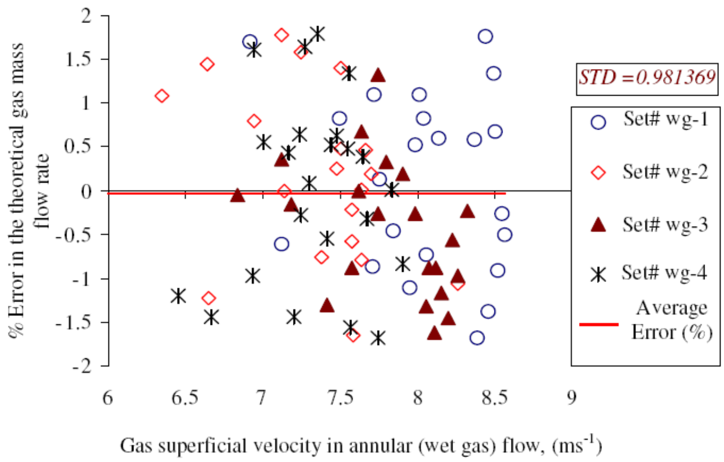


Figure 15: The percentage error in the predicted gas mass flow rates for all sets of data ($C_{dg,wg} = 0.932$ and the standard deviation, *STD* = 0.981369)

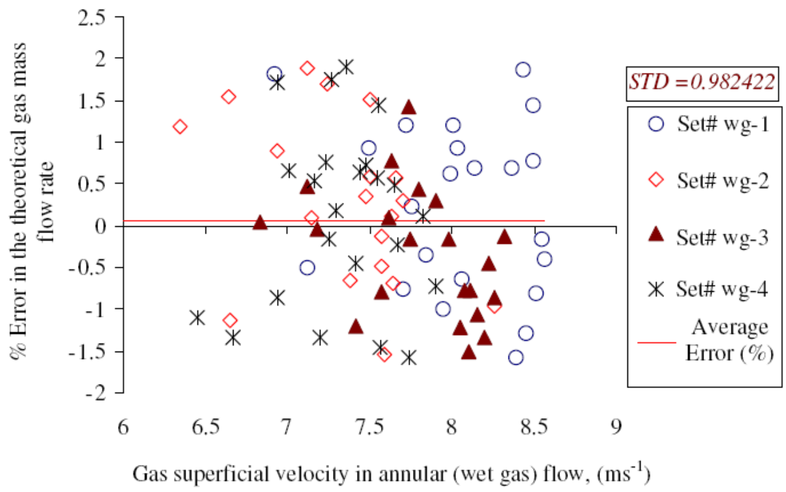


Figure 16: The percentage error in the predicted gas mass flow rates for all sets of data ($C_{dg,wg} = 0.933$ and the standard deviation, *STD* = 0.982422)

6. Conclusions

The results reported in the present paper indicate that a Conductance Multiphase Venturi Meter (CMVM) can be used for the measurement of the gas flow rate in annular gas-water two phase flows (wet gas flows). An advanced CMVM was designed and tested successfully which is capable of measuring the gas volume fraction at the inlet and the throat of the Venturi. It was found, in general, that the gas volume fraction α_1 at the inlet of the Venturi is grater than the gas volume fraction α_2 at the throat of the Venturi. The optimum value of the gas discharge coefficient in which a minimum percentage error in the predicted gas mass flow rate (i.e. -0.0428%) can be achieved was 0.932. A new model was also investigated which depends on the gas volume fraction at the inlet and the throat of the Venturi instead of just relaying on the prior knowledge of the mass flow quality x. online measurement of the mass flow quality x is rather difficult and not practical in multiphase flow applications.

7. References

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